A possibility of increasing spin injection efficiency in magnetic junctions

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Abstract

Nonequilibrium electron spin polarization is calculated under spin injection from one ferromagnet to another in magnetic junction. It is shown that the nonequilibrium spin polarization can be comparable with equilibrium one if the material parameters are chosen appropriately. This leads to lowering the threshold current density necessary for the junction switching and opens a perspective to creating THz laser based on the spin-polarized current injection.

The pioneer work by Aronov and Pikus [1] marked the beginning of vast literature devoted to the problem of spin injection under current flowing through the interface between a ferromagnet (F) and nonmagnetic conductor (N) or another ferromagnet [2]–[27]. Such an attention is due to several reasons. First, there is a perspective of creating spin analogs of transistor type semiconductor devices in which charge injection is replaced by spin injection. Spin injection determines also the giant magnetoresistance effect in spin-valve type systems (see, e.g., [5, 7, 9, 28]) and the fluctuation instability effect in such systems under high enough current density through the contact between ferromagnets that leads to switching from antiparallel configuration to parallel one [29, 30]. Finally, if the spin subband population inversion by injection is reached, the amplifiers and generators for 10^{12}–10^{13} Hz frequency range may be created. In this connection, note Ref. [31], where spin injection effect on the microwave absorption and emission in nonmagnetic semiconductor n-InSb was observed, as well as Ref. [32], in which a possibility is discussed of creating a solid-state THz laser based on the spin-polarized electron tunnel injection from one ferromagnet to another.

In the present paper we try to show that a significant (by several orders of magnitude) increasing the injected nonequilibrium spin density is possible under appropriate parameter choice. Such a possibility was not perceived in

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Refs. [2]–[27], because symmetric $F/N/F$ type structures were considered there with collinear relative orientation of the same ferromagnetic layers.

Let us consider a $F_1/F_2/N$ system consisting of three contacting layers — a semi-infinite ferromagnetic layer 1 in $-\infty < x < 0$ range, a ferromagnetic layer 2 of finite thickness L in $0 < x < L$ range, and a semi-infinite nonmagnetic layer 3 in $L < x < \infty$ range. When electric current flows in the x axis positive direction ($1 \to 2 \to 3$), the spin polarization degree changes near the interfaces. The measure of the spin polarization is $P(x) = (n_+(x) - n_-(x))/n$, where $n_\pm(x)$ are partial spin-up and spin-down electron densities, $n = n_+(x) + n_-(x)$ is total electron density that is assumed to be constant (independent of x) because of neutrality condition. The polarization deviation $\Delta P(x) = P(x) - \bar{P}$ from the equilibrium value $\bar{P}$ in each of the layers is described by a steady-state spin-current continuity equation [33]

$$\frac{dJ(x)}{dx} + \frac{\hbar n}{2\tau}\Delta P(x) = 0, \tag{1}$$

where τ is effective longitudinal spin relaxation time, which is related with corresponding partial quantities by $\tau^{-1} = \tau_+^{-1} + \tau_-^{-1}$, $J(x)$ is spin current density defined as $J(x) = (\hbar/2e)\,(j_+(x) - j_-(x))$, where $j_\pm(x)$ are partial electric current densities, $j = j_+(x) + j_-(x)$ is total electric current density that is assumed to be constant because of the one-dimensional geometry of the problem.

In the two spin subband model, the partial currents take the form

$$j_\pm = e\mu_\pm n_\pm(x)E(x) - eD_\pm \frac{dn_\pm(x)}{dx}, \tag{2}$$

where $E(x)$ is local electric field, $\mu_\pm$ and $D_\pm$ are partial electron mobilities and diffusion constants, respectively; they are assumed to be invariable under breaking spin equilibrium.

By expressing $E(x)$ in terms of the current density j and taking the $n_\pm(x) = (n/2)\,(1 \pm P(x))$ relation into account, we obtain the following formula for the spin current:

$$\begin{aligned} &J(x) = (\hbar/2e)\,[1 + (en/2\sigma)(\mu_+ - \mu_-)\Delta P(x)]^{-1} \\ &\times\Big\{[Q + (en/2\sigma)(\mu_+ + \mu_-)\Delta P(x)]\,j \\ &-en\left[\tilde{D} + (en/2\sigma)(\mu_+ D_- - \mu_- D_+)\Delta P(x)\right]\frac{d\Delta P(x)}{dx}\Big\}, \end{aligned} \tag{3}$$

where $\sigma = \sigma_+ + \sigma_-$ and $\sigma_\pm = e\mu_\pm \bar{n}_\pm$ are the total and partial conductivities in spin equilibrium state, respectively, $\bar{n}_\pm$ are equilibrium partial electron densities in the spin subbands, $Q = (\sigma_+ - \sigma_-)/\sigma$ is the conduction spin polarization, $\tilde{D} = (D_+\sigma_- + D_-\sigma_+)/\sigma$ is effective spin diffusion constant.

At $|\Delta P| \ll 1$ we have in linear approximation

$$J(x) = \frac{\hbar}{2e}\left\{Qj - en\tilde{D}\frac{d\Delta P(x)}{dx} + \frac{en\tilde{\mu}}{\sigma}j\Delta P(x)\right\}, \tag{4}$$

where $\tilde{\mu} = (\mu_+\sigma_- + \mu_-\sigma_+)/\sigma$ is effective spin mobility. It can be shown easily that the ratio of the third summand in Eq. (4) to the second one has an order of j/j_D, where $j_D = enl/\tau$ is diffusion current density. At the parameter values typical for metals we have $j_D \sim 10^{10}\,\mathrm{A/cm^2}$, so that $j/j_D \ll 1$ at attainable current densities, and the last (drift) term in Eq. (4) can be neglected. Then the substitution of Eq. (4) into (1) gives the steady-state diffusion equation for nonequilibrium spins:

$$\frac{d^2\Delta P(x)}{dx^2} - \frac{\Delta P(x)}{l^2} = 0, \tag{5}$$

where $l = \sqrt{\tilde{D}\tau}$ is spin diffusion length.

Equations (4) and (5) have been derived in the approximation of small deviation from spin equilibrium ($|\Delta P| \ll 1$) [33]. Note that Eqs. (4) (without the drift term) and (5) retain their form at any deviation from spin equilibrium also under some often used model assumptions (the same partial mobilities and diffusion constants, neglecting the effect of spin equilibrium breakdown on the partial conductivities).

The following boundary conditions take place under spin-polarized current flowing through interface between two ferromagnets 1 and 2 in $1 \to 2$ direction [33, 30]:

$$J_1 \cos\chi = J_2, \tag{6}$$

$$N_1 \Delta P_1 = N_2 \Delta P_2 \cos\chi, \tag{7}$$

where $N = (n/2)\left(g_+^{-1} + g_-^{-1}\right)$, $g_\pm$ are partial densities of states at the Fermi level in spin subbands, χ is the angle between the magnetization vectors of the contacting layers.

Presence of the $\cos\chi$ multiplier in the boundary conditions is due to change of the quantization axis under electron passing from one magnetic layer to another. Under passing from a magnetic layer to nonmagnetic one (or vise versa), there is no such change, so that $\cos\chi = 1$ is to be put.

The solution of Eq. (5) with boundary conditions (6), (7) describing the distribution of the nonequilibrium spin polarization $\Delta P(x)$ in layer 2 takes the form [30]

$$\begin{aligned}\Delta P(x) = (j/j_{D2})&\Big[\sinh\lambda + \nu_{23}\cosh\lambda + (1/\nu_{12})\cos^2\chi(\cosh\lambda + \nu_{23}\sinh\lambda)\Big]^{-1}\\ \times\Big\{&(Q_1\cos\chi - Q_2)[\cosh(\lambda-\xi) + \nu_{23}\sinh(\lambda-\xi)]\\ +&Q_2\left(\cosh\xi + (1/\nu_{12})\cos^2\chi\sinh\xi\right)\Big\},\end{aligned} \tag{8}$$

where $\lambda = L/l_2$, $\xi = x/l_2$. The parameters $\nu_{12} = (j_{D2}/j_{D1})(N_1/N_2)$ and $\nu_{23} = (j_{D3}/j_{D2})(N_2/N_3)$ describe the spin current matching in the interface. They may be presented as a ratio of "spin resistances" [34]:

$$\nu_{ik} = \frac{Z_i}{Z_k}, \qquad Z = \frac{\rho l}{1-Q^2}, \qquad \rho = \frac{1}{\sigma}. \tag{9}$$

At $Z_1 \gg Z_2$ the cathode layer 1 works as an ideal injector, in which the spin polarization is equilibrium ($\Delta P = 0$), while the spin equilibrium breakdown occurs in the anode layer 2. In the opposite case, $Z_1 \ll Z_2$, an ideal collector regime takes place, when the spin equilibrium is disturbed in layer 1 and remains unchanged in layer 2.

In Refs. [2]–[27] the injection from ferromagnetic metal to semiconductor was considered, when $Z_1 \ll Z_2$, as well injection from a ferromagnetic metal to the same metal with antiparallel orientation of the magnetic moment ($Z_1 = Z_2$, $\chi = 180°$). In those cases, $\Delta P \leq j/j_D \ll 1$, so that the injection efficiency is rather low [4].

Let us consider the case of thin layer 2 ($\lambda \ll 1$). The Eq. (8) takes the form

$$\Delta P(x) = \frac{j}{j_{D2}} \frac{Q_1 \nu_{12} \cos\chi}{\nu_{12}\nu_{23} + \cos^2\chi}. \tag{10}$$

As it was noted, j/j_{D2} ratio is small usually. However, the second multiplier in the right-hand side of Eq. (10) can take large value at $\nu_{12} \gg 1$, $\nu_{12}\nu_{23} \ll 1$ (or $Z_2 \ll Z_1 \ll Z_3$). Therefore, in spite of the smallness of the j/j_{D2} ratio, the ΔP quantity can be comparable with $\bar{P}$. Such an effect allows a simple physical interpretation. Under fulfillment of the conditions indicated, effective injection from layer 1 to layer 2 takes place, while the injection from layer 2 to layer 3 is "locked". The dependence of ΔP on χ has the form of a resonance line in that case (see Fig. 1). At $j \sim 10^7$ A/cm^2, $j_{D2} \sim 10^{10}$ A/cm^2, $\nu_{12} = 100$, $\nu_{23} = 0.0001$ we have $|\Delta P| \sim 10^{-1}$ that is comparable with the equilibrium electron spin polarization in ferromagnets [35].

To realize the conditions $Z_2 \ll Z_1 \ll Z_3$ corresponding to high spin injection efficiency, a half-metal [36] may be chosen for the layer 1, in that case spin resistance Z_1 is high because the conduction spin polarization Q_1 is close to 1 (see Eq. (9)). Semiconductor with large Z_3 value may be taken for the nonmagnetic layer 3. Large Z_3 value may be achieved in the case due to high resistivity and larger spin diffusion length. The layer 2 in which nonequilibrium spin polarization appears may be a ferromagnet such as cobalt.

An important consequence of the increasing spin injection efficiency is lowering the threshold of the lattice magnetization fluctuation instability under spin-polarized current flowing through the magnetic junction. Indeed, the *sd* exchange interaction effective field is proportional to a derivative of the integral of $\Delta P(x)$ over the layer thickness with respect to $\cos\chi$ [29, 30]. Therefore, increasing of ΔP at $\chi = 0$ and $\chi = 180°$ under dominating injection instability mechanism leads to lowering the instability threshold and, consequently, the current density necessary for switching the junction antiparallel configuration to parallel one [30]. Besides, as is seen from the figure, $\Delta P(x)$ changes quickly near $\chi = 90°$ under sweeping the angle χ. Therefore, it may be expected that the switching will be much quicker under the conditions indicated.

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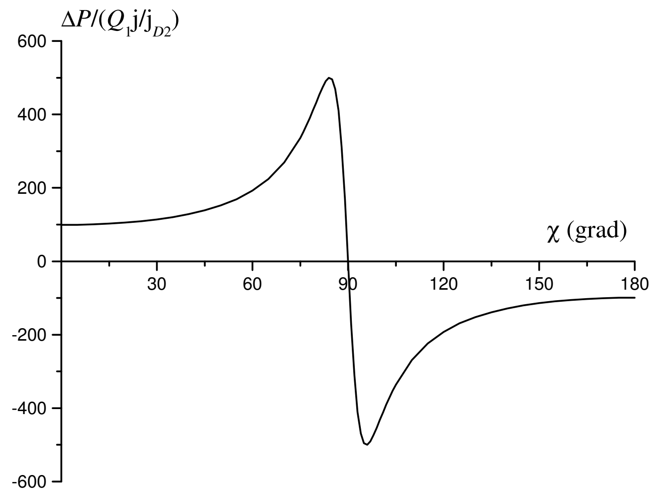

Figure 1: The dependence of the nonequilibrium electron spin polarization on the angle χ at $\nu_{12} = 100$, $\nu_{23} = 0.0001$.

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